

Hypernuclear Physics at $\bar{\text{PANDA}}$

Experimental Challenges

P. Achenbach · S. Bleser · J. Pochodzalla ·
A. Sanchez Lorente · M. Steinen

Received: 20 September 2011 / Accepted: date

Abstract Hypernuclear research will be one of the main topics addressed by the $\bar{\text{PANDA}}$ experiment at the planned Facility for Anti-proton and Ion Research FAIR at Darmstadt, Germany. A copious production of Ξ -hyperons at a dedicated internal target in the stored anti-proton beam is expected, which will enable the high-precision γ -spectroscopy of double strange systems for the first time. In addition to the general purpose $\bar{\text{PANDA}}$ setup, the hypernuclear experiments require an active secondary target of silicon layers and absorber material as well as high purity germanium (HPGe) crystals as γ -detectors. The design of the setup and the development of these detectors is progressing: a first HPGe crystal with a new electromechanical cooling system was prepared and the properties of a silicon strip detector as a prototype to be used in the secondary target were studied. Simultaneously to the hardware projects, detailed Monte Carlo simulations were performed to predict the yield of particle stable hypernuclei. With the help of the Monte Carlo a procedure for $\Lambda\Lambda$ -hypernuclei identification by the detection and correlation of the weak decay pions was developed.

Keywords Strangeness · Double hypernuclei · HPGe detectors

Supported by the Research Infrastructure Integrating Activity “Study of Strongly Interacting Matter” HadronPhysics2 (SPHERE) under the 7th Framework Programme of EU. We acknowledge financial support from the Bundesministerium für Bildung und Forschung (bmb+f) under contract number 06MZ9182.

P. Achenbach · S. Bleser · J. Pochodzalla · M. Steinen
Institut für Kernphysik, Johannes Gutenberg-Universität
J.J.-Becherweg 45, D-55099 Mainz, Germany
E-mail: patrick@kph.uni-mainz.de

A. Sanchez Lorente
Helmholtz-Institut Mainz
D-55099 Mainz, Germany

1 Introduction

The “standard model” is the fundamental theory which unites weak, electromagnetic, and strong interactions. Strong processes are formulated in Quantum Chromodynamics (QCD), the field theory for the dynamics of quarks and gluons. QCD has been thoroughly probed in strong interactions at very high energies. However, at the energy scale of the nucleon mass hadrons are complex many-body systems. Even though they interact strongly, the description by the fundamental QCD equations is complicated by the non-perturbative nature of the theory. The investigation of strange hadrons carrying an additional flavour degree-of-freedom is essential for understanding the low-energy regime of QCD.

A very interesting phenomenon in nuclear physics is the existence of nuclei containing strange baryons. The lightest hyperons are stable against strong and electromagnetic decays, and as they do not suffer from Pauli blocking by other nucleons they can live long enough in the nuclear cores to become bound. When a hyperon, specifically a Λ -hyperon, replaces one of the nucleons in the nucleus, the original nuclear structure changes to a system composed by the hyperon and the core of the remaining nucleons. The existence of double strange nuclear systems like Ξ^- or $\Lambda\Lambda$ hypernuclei is directly linked to the strength of the attractive hyperon–nucleon (YN) and unknown hyperon–hyperon (YY) interactions. Models for the YY interactions have been constructed from the expansion of the NN interaction and limited YN scattering data. This approach needs to be validated against double hypernuclei binding energies and excitation spectra.

The study of strange nuclear systems provides invaluable information on both, on the structure of nuclei as many-body hadronic systems and on strange baryons in the nuclear medium. Although single and double Λ -hypernuclei were discovered many decades ago in cosmic ray interactions studied by the emulsion technique, only few double Λ -hypernuclear isotopes are presently known. In particular, $\Lambda\Lambda$ -hypernuclei formed in anti-proton beams are the only practical systems among all strange baryons for investigating the strong nuclear interaction.

2 Production and detection of hypernuclei at $\bar{\text{P}}\text{ANDA}$

The planned Facility for Anti-proton and Ion Research (FAIR) near Darmstadt will include the High Energy Storage Ring (HESR) to store anti-protons of several GeV/ c momentum in an intense and high quality beam. With a dedicated internal target in the storage ring a copious production of Ξ -hyperons is expected which can be stopped in dedicated absorbers to form bound states of Ξ hypernuclei. The latter can be used as a gateway to form $\Lambda\Lambda$ hypernuclei, which will enable the high-precision γ -spectroscopy of double strange systems for the first time [1,2].

The $\bar{\text{P}}\text{ANDA}$ experiment (AntiProton ANnihilations at DArmstadt) planned at the HESR storage ring is a next-generation hadron physics experiment. In addition to the general purpose $\bar{\text{P}}\text{ANDA}$ setup for charged particle detection, the hypernuclear experiments require an active secondary target of silicon layers and absorber material

in addition to high purity germanium (HPGe) crystals as γ -detectors. Some technical and practical aspects currently being studied by the PANDA hypernuclear groups are

1. design and fabrication of the primary target,
2. design and development of the secondary target, and
3. design and operation of the HPGe γ -array.

In the following we highlight some of the experimental challenges in realizing the setup. The expected performance of the proposed experiment with this setup was simulated with the help of a micro-canonical decay model was predicting the yield of particle stable double hypernuclei.

3 The challenge for a nuclear internal storage ring target

On a nuclear internal target low momentum Ξ pairs can be produced in $\bar{p}p \rightarrow \Xi^- \bar{\Xi}^+$ or $\bar{p}n \rightarrow \Xi^- \bar{\Xi}^0$ reactions. The advantage at HESR in the Ξ production rate as compared to kaon beam induced reactions is the fact that the anti-proton is stable and can be retained in the storage ring. The largest \bar{p} production rate achievable at HESR is of the order of $10^7 \bar{p}/s$ with a maximum of approximately 10^{11} stored anti-protons in the HESR ring [2]. This allows a rather high luminosity even with very thin primary targets, either with the standard hydrogen target of the PANDA experiment, or with a dedicated target for hypernuclear spectroscopy.

The beam-target interactions will reduce the life-time of the stored anti-proton beam. Consequently, a reasonable compromise between \bar{p} beam preparation time and beam loss rate during one HESR cycle needs to be found. Obviously, this compromise is dependent on the target material and thickness. The possibility of steering a low density region of the transverse beam profile over the target along with the gradual consumption of anti-protons will be an important feature. These are conditions posing a real challenge for the design of the nuclear internal target inside the storage ring.

At present, techniques for the manufacturing of μm -thin synthetic diamond filaments cut from a membrane as internal target are being explored [3]. Synthetic diamonds can be grown from a hydrocarbon gas mixture by chemical vapour deposition and can be supported by a silicon ring structure matching the beam pipe. The thermal conductivity of synthetic diamond is very high that prevents the materials from overheating. The lateral size of the synthetic diamond filament could be of the order of $100 \mu\text{m}$ or less. The target could be designed with an empty region inside the support ring providing space during beam preparation and for the high-density beam center during the anti-proton storage. Such geometries can be made very precisely by cutting the diamond membrane with fs-pulsed high-powered lasers [3].

4 The challenge for an active high-resolution Ξ -absorber target

The main purpose of the active high-resolution Ξ -absorber target is the tracking and stopping of the produced cascade hyperons and their decay products. The active part of the secondary target will be made from silicon strip sensors. The slowing down

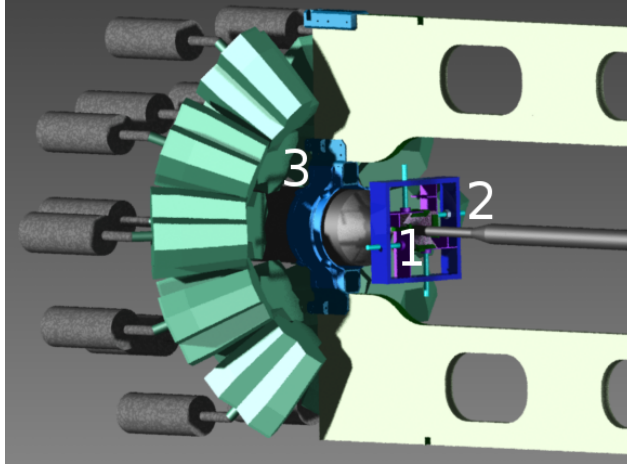


Fig. 1 Scheme of the hypernuclear setup inside $\bar{\text{P}}\text{ANDA}$. In the backward region of the spectrometer a dedicated synthetic diamond target will be installed inside a beam pipe of reduced diameter (1). A mechanical support structure surrounds this target and holds the active Ξ -absorber target (2). A compact γ -array with maximized solid-angle acceptance will be used to detect radiative de-excitations (3).

of the Ξ^- proceeds by energy-loss during the passage through additional absorber layers. If decelerated to rest before decaying, the Ξ^- can be captured inside a nucleus, eventually releasing two Λ hyperons and forming a double hypernuclei. The geometry of the target is essentially determined by the life-time of the hyperons and their stopping time in silicon and the absorber materials.

In analogy to the germanium detectors array, the silicon detector has to be able to operate in extreme conditions such as a large hadronic environment since it is close to the interaction point. Furthermore, the material budget on the detector volume must be kept low. The feasibility of such a device has recently been studied in Mainz with a single sided microstrip sensor with a strip pitch of $50\,\mu\text{m}$ and $2\times 2\,\text{cm}^2$ size. In addition, studies on ultra-thin cables based on adhesive-less aluminium-polyimide foiled dielectrics, the 128-channel APV-25-S1 front-end chip [4], the modified electronics board, and the mechanics of the target are being performed.

5 The challenge for a compact γ -array inside the $\bar{\text{P}}\text{ANDA}$ setup

High purity germanium (HPGe) detectors are key instruments in nuclear structure physics for detecting the radiative de-excitation of excited nuclei. Typically, the crystals are cooled with liquid nitrogen and operated in the temperature range of 77–115 K. The requirement of minimal distance of the secondary target from the interaction point combined with the necessary support structures nested inside the $\bar{\text{P}}\text{ANDA}$ target spectrometer leaves very restricted space for the installations of the hypernuclear physics setup. The situation is displayed in Fig. 1, showing the anti-proton beam pipe surrounded by the targets and an γ -array of 15 n-type HPGe triple cluster detectors.

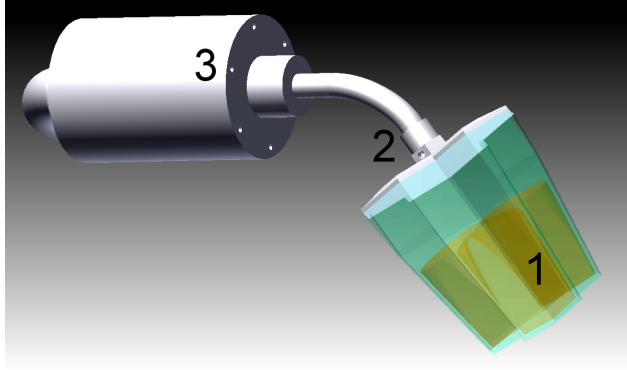


Fig. 2 Drawing of one HPGe detector system assembled to an X-Cooler II device. Three encapsulated coaxial HPGe crystals (1) are arranged in one capsule. The flexible section of the thick cold finger (2) enables the placement of the cluster at the restricted space inside the $\bar{\text{P}}\text{ANDA}$ spectrometer. The X-Cooler II (3) replaces the standard liquid nitrogen cooling devices.

For an effective integration of the array into the $\bar{\text{P}}\text{ANDA}$ spectrometer an electromechanical cooling device will be used instead of liquid nitrogen with its bulky dewars. Composite detectors made of three large volume encapsulated Ge crystals and cooled by the electromechanical cooling device X-Cooler II by ORTEC are being considered. Fig. 2 shows the drawing of a triple HPGe cluster assembled to an X-Cooler II device. The individual Ge crystals are sealed in an aluminium can and installed in a common vacuum cryostat. An intermediate thermal shield may be applied in order to act as a heat reflector thus reducing the heating of the encapsulated Ge crystals.

The energy resolution of such a system with electromechanical cooling has been determined with a standard ^{60}Co calibration source and a line width of 1.97 keV for the 1.332 keV γ -line was found, see Fig. 3. In comparison to a cooling device based on liquid nitrogen where a line width of 1.86 keV was measured, the electromechanical cooling seems to have no negative impact on the performance [5].

Another major challenge at $\bar{\text{P}}\text{ANDA}$ is the operation of the germanium detectors close to a strong magnetic field over long periods. It was demonstrated that a good energy resolution can be preserved up to 1 T [6].

6 Performance of the proposed hypernuclear experiment

The production of excited states in $\Lambda\Lambda$ hypernuclei was studied following the micro-canonical break-up of an initially excited double hypernucleus created by the absorption and conversion of a stopped Ξ^- hyperon [7, 8]. In these calculations the formation of excited states dominates. Furthermore, different double hypernuclei isotopes which depend on the initial target nuclei are formed. Thus, the ability to assign the observable γ -transitions in a unique way to a specific double $\Lambda\Lambda$ hypernucleus seems possible.

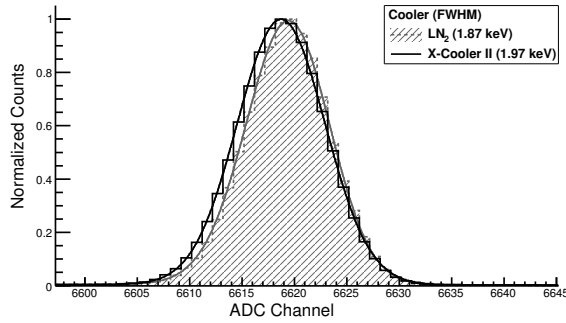


Fig. 3 Measured energy spectra of the 1.332 keV line of a ^{60}Co calibration source taken with two different cooling devices. For the dashed spectrum with a line width of $\text{FWHM} = 1.97 \text{ keV}$ the HPGe crystal was cooled electromechanically, for the solid spectrum with a line width of $\text{FWHM} = 1.87 \text{ keV}$ a liquid nitrogen cooling system was used [5].

The non-mesonic and mesonic decays of the light hypernuclei to be studied in the initial phase of the planned experiments are of similar magnitude. The analysis strategy will make use of the two-body pionic decays, where the mono-energetic pions will leave a unique signature in the secondary target. In the case of two sequential mesonic weak decays of the double hypernuclei, the momenta of the two pions are strongly correlated. Thus, a coincidence measurement in the active Ξ -absorber target will provide an effective method to tag the production of a double hypernucleus.

7 Conclusions

At the $\overline{\text{PANDA}}$ experiment at FAIR it will become possible to explore the level scheme of low-mass isotopes of double hypernuclei for the first time. The spectroscopic information will be obtained via γ -ray detection using an array of 15 n-type HPGe triple cluster detectors located near a dedicated arrangement of targets: a primary diamond target at the entrance to the central tracking detector of $\overline{\text{PANDA}}$, and a small secondary active target composed of silicon detectors and absorbers to decelerate and stop Ξ -hyperons and to identify the weak decay products.

References

1. J. Pochodzalla, Nucl. Instr. and Meth. in Phys. Res. **B 214**, 149 (2004)
2. $\overline{\text{PANDA}}$ Collaboration, Physics Performance Report for $\overline{\text{PANDA}}$: Strong Interaction Studies with Antiprotons (2009). arXiv:0903.3905
3. F. Iazzi, Double Hypernuclei: Internal Target Report (2011). PANDA Meeting, GSI, 5 Sept. 2011
4. G.F. Dalla Betta, et al., Nucl. Instr. and Meth. in Phys. Res. **A 460**, 306 (2001)
5. M. Steinen, Optimierung von elektrisch gekühlten Germanium-Detektoren für das $\overline{\text{PANDA}}$ -Experiment. Diploma thesis, Johannes Gutenberg-Universität Mainz (2011)
6. A. Sanchez Lorente, et al., Nucl. Instr. Meth. Phys. Res. **A 573**, 410 (2007)
7. A. Sanchez Lorente, J. Pochodzalla, A. Botvina, Int. J. Mod. Phys. **E 19**, 2644 (2010)
8. A. Sanchez Lorente, A.S. Botvina, J. Pochodzalla, Phys. Lett. **B 697**, 222 (2011)